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# Microlensing and Halo Cold Dark Matter

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## ABSTRACT

We discuss the implications of the more than 50 microlensing events seen by the EROS, MACHO, and OGLE collaborations for the composition of the halo of our galaxy. The event rates indicate that the halo mass fraction in MACHO's is less than 30%, consistent with expectations for a universe whose primary component is cold dark matter. We caution that the uncertainties are such that a larger MACHO fraction cannot yet be excluded.

In 1986 Paczynski suggested microlensing as a probe of dark (or very faint) stars in our galaxy [1] (referred to generically as MAssive Compact Halo Objects, or MACHOs). In the past year more than 50 microlensing events have been reported. (For microlensing the two images are too close to be resolved; instead, the combined light leads to an achromatic, time-symmetric brightening.) The EROS collaboration has seen two events in the direction of the Large Magellanic Cloud (LMC) [2]; the OGLE collaboration has seen 12 events in the direction of the galactic bulge [3]; and the MACHO collaboration has seen three events in the direction of the LMC and more than 40 in the direction of the galactic bulge [4].

The study of microlensing toward the galactic bulge mainly probes the structure of the inner galaxy, while microlensing toward the LMC mainly probes the dark halo [1, 5]. The probability that a given star is being microlensed by a foreground object is referred to as the optical depth for microlensing ( $\equiv \tau$ ). Expectations for the bulge were  $\tau_{\text{BULGE}} \simeq 1 \times 10^{-6}$ , largely due to lower-main-sequence stars in the disk [6]; OGLE reports an optical depth that is about a factor of three larger,  $\tau_{\text{OGLE}} = 3.3 \pm 1.2 \times 10^{-6}$  [3], and the rate observed by MACHO may be even higher [7]. Expectations for an all-MACHO halo were  $\tau_{\text{LMC}} \simeq 5 \times 10^{-7}$  [5] (because data poorly constrain the halo, uncertainties in this estimate are large, almost a factor two either way [8, 9, 10]). Based upon 9 million-star years of observations, the three events observed, and estimates of their efficiencies (between 20% and 40%) [11], the MACHO data indicate that  $\tau_{\text{MACHO}} \simeq 1 \times 10^{-7}$ . The EROS data indicate a similar optical depth [2].

Evidence that spiral galaxies, including our own, are embedded in extended, dark (roughly spherical) halos comes from galactic rotation curves, the study of satellite galaxies and binary galaxies, the kinematics of the globular clusters in our galaxy, the warping of galactic disks, and the flaring of neutral hydrogen gas associated with disks [12, 13, 14]. Galactic halos are repositories for both nonbaryonic dark matter (mainly slowly moving particles, or cold dark matter, since fast moving particles such as light neutrinos move too fast to be captured) and baryonic dark matter. Experimental efforts to detect nonbaryonic dark matter have focussed on our own halo [15]. Determining the mass fraction of the halo in baryons is crucial for estimating the amount of nonbaryonic matter that may exist in our galaxy.

Our purpose here is to use the microlensing data to draw conclusions about the MACHO fraction of the halo—and from it the fraction of the halo that could be particle dark matter. Since the expected microlensing rate in the direction of the LMC depends upon galactic modelling [8, 9, 10] and the LMC microlensing statistics are small, we adopt the following strategy. The rotation curve, local projected mass density, distribution of luminous material in the disk and bulge, and bulge microlensing rate are used to constrain the halo model. For acceptable galactic models we calculate  $\tau_{\text{LMC}}$ , and then, based upon the observed LMC rate, make inferences about the MACHO fraction of the halo, concluding that it must be less than about 30%.

Models of the Milky Way have three major components [16], a central bulge, a disk, and a spherical halo, with large uncertainties in the parameters that define all three. The basic picture of the bulge has evolved from spherical to recent indications that it may be closer to a bar [17]. We follow Dwek et al. [18] who have utilized DIRBE surface brightness

observations to construct a triaxial bulge model:

$$\rho_{\text{BAR}} = \frac{M_0}{8\pi abc} e^{-s^2/2}, \quad s^4 = \left[ \frac{x^2}{a^2} + \frac{y^2}{b^2} \right]^2 + \frac{z^4}{c^4}, \quad (1)$$

where the bulge mass  $M_{\text{BAR}} = 0.82M_0$ , the scale lengths  $a = 1.49 \text{ kpc}$ ,  $b = 0.58 \text{ kpc}$  and  $c = 0.40 \text{ kpc}$ , and the long axis is oriented at an angle of about  $10^\circ$  with respect to the line of sight toward the galactic center. The bulge mass is not well determined, and we consider  $M_{\text{BAR}} = 1, 2, 3$ , and  $4 \times 10^{10} M_\odot$  [16, 19].

The bulk of the luminous matter in the disk follows a double exponential distribution [20]. There is some evidence that the disk has both a “thick” and a “thin” component [20]. We take the sum of a “fixed,” thin luminous disk,

$$\rho_{\text{LUM}}(r, z) = \frac{\Sigma_{\text{LUM}}}{2h} \exp[-(r - r_0)/r_d] e^{-|z|/h}, \quad (2)$$

with scale length  $r_d \sim 3.5 \text{ kpc}$ , scale height  $h = 0.3 \text{ kpc}$ , and local projected mass density  $\Sigma_{\text{LUM}} = 25 M_\odot \text{ pc}^{-2}$  [21], a “variable” component. For the variable component we use the same scale length, but vary the thickness, very thin ( $h = 0.15 \text{ kpc}$ ), thin ( $h = 0.3 \text{ kpc}$ ) and thick ( $h = 1.5 \text{ kpc}$ ), and local projected mass density  $\Sigma_{\text{VAR}}$ . We also explore a variable component whose surface density scales as  $1/r$  rather than exponentially [23]. A number of studies of stars motions constrain the local projected mass density within a distance of  $0.3 \text{ kpc} - 1.1 \text{ kpc}$  of the galactic plane [22]. As a conservative bound we require that  $\Sigma_{\text{TOT}}(1 \text{ kpc}) = \int_{-1 \text{ kpc}}^{1 \text{ kpc}} \rho(r_0, z) dz = 25 - 100 M_\odot \text{ pc}^{-2}$ ; this implies the variable component of the disk must satisfy  $\Sigma_{\text{VAR}}(1 \text{ kpc}) \leq 75 M_\odot \text{ pc}^{-2}$ .

The third component is the halo. We assume independent isothermal distributions for the MACHOs and cold dark matter with core radii  $a_i = 2, 4, 8$ , and  $16 \text{ kpc}$ ,

$$\rho_{\text{HALO},i} = \frac{a_i^2 + r_0^2}{a_i^2 + r^2} \rho_{0,i}, \quad (3)$$

where  $i = \text{MACHO}$ , cold dark matter and  $\rho_{0,i}$  is the local mass density of component  $i$ . More complex halo models are possible; e.g., flattened halos [9, 10]. We do not expect such refinements to significantly alter our basic conclusions; they only serve to increase slightly the theoretical uncertainties.

The average optical depth for microlensing a distant star by a foreground star is [5]

$$\tau = \frac{4\pi G}{c^2} \frac{\int_0^\infty ds \rho(s) \int_0^s dx \rho(x) x(s-x)/s}{\int_0^\infty ds \rho(s)}, \quad (4)$$

where  $\rho$  is the mass density in stars,  $s$  is the distance to the star being lensed, and  $x$  is the distance to the lens [24]. In estimating the optical depth toward the bulge, we consider lensing of bulge stars by both disk and bulge objects; for the LMC we consider lensing of LMC stars by halo and disk objects. We have assumed that the threshold for the detection of microlensing is a brightening of 1.34 (which roughly corresponds to the experimental

thresholds). Further, while the microlensing rate more closely describes what is measured, it depends upon detailed knowledge of the velocity distribution of the lenses, and previous analyses [8, 9] have found that optical depth correlates well with lensing rate.

Kinematic constraints to the galactic model come from the circular rotation speed at our position ( $\equiv v_c$ ) and the requirement that the rotation curve be approximately flat between about 4 kpc and 18 kpc. We adopt the IAU value of  $220 \text{ km s}^{-1}$  for  $v_c$  with an uncertainty of  $\pm 20 \text{ km s}^{-1}$ , and we take our distance from the galactic center to be  $r_0 = 8.0, 8.5$ , and  $9.0$  kpc. For the flatness constraint we follow our previous work [8] in requiring that the total variation in  $v(r)$  be less than 14% over the aforementioned range.

We construct our suite of viable models as follows. Starting with a disk (exponential or  $1/r$ ) with local surface density  $\Sigma_{\text{VAR}}$  and a bulge of mass  $M_{\text{BAR}}$  we compute  $\tau_{\text{BULGE}}$ , the optical depth to Baade’s window, galactic coordinates  $(1^\circ, -4^\circ)$ , and the contributions of the disk and bulge to the rotation curve at  $r = r_0$ . For a choice of halo parameters this then determines the local halo density, the full rotation curve, and the optical depth to the LMC. We deem a model viable if: (a)  $\tau_{\text{BULGE}} \geq 2.0 \times 10^{-6}$ , (b) the rotation curve is sufficiently flat, and (c)  $\tau_{\text{LMC}}$  is in the range  $0.5 - 2.0 \times 10^{-7}$ . The last condition primarily constrains the baryonic mass fraction and does not eliminate many models.

Our results are summarized in Figs. 1-4. We find that in general the disk alone does not provide sufficient lensing to explain the event rate seen toward the bulge. While  $\tau_{\text{BULGE}}$  increases with  $\Sigma_{\text{VAR}}$ ,  $\Sigma_{\text{VAR}}$  reaches its upper bound of  $75 M_\odot \text{ pc}^{-2}$  or the rotation-curve constraint is violated before  $\tau_{\text{BULGE}} = 2 \times 10^{-6}$ . For fixed  $\Sigma_{\text{VAR}}$  the disk density along the line of sight is about the same, and the difference between a thick and thin disk is negligible. However, there is less mass in a thin disk and a larger  $\Sigma_{\text{VAR}}$  is permitted without violating the rotation-curve constraint. A very thin disk ( $h = 0.15 \text{ kpc}$ ) does not help further: the line of sight to Baade’s window passes above most of the disk material. The results for disks with a  $1/r$  density distribution are not significantly different from those of exponential disks.

The bar is a much more efficient source of lensing [25]. In all viable models a bar mass of at least  $2 \times 10^{10} M_\odot$  is required; if  $\tau_{\text{BULGE}}$  is determined to be greater than  $3 \times 10^{-6}$ , as may well be the case, a bar mass of at least  $3 \times 10^{10} M_\odot$  seems unavoidable. Should the optical depth be  $4 \times 10^{-6}$ , a bar mass of  $4 \times 10^{10} M_\odot$  may be indicated. We note that even higher bar masses ( $M_{\text{BAR}} \geq 5 \times 10^{10} M_\odot$ ) make it difficult to achieve a flat rotation curve interior to the solar radius and thus are not viable.

Turning now to the optical depth to the LMC (Fig. 2), we find as expected that a thin disk makes a negligible contribution to  $\tau_{\text{LMC}}$ , while a thick disk can provide a significant contribution (toward the LMC  $\tau \propto h$ ). In fact, a model with a heavy bar and a thick disk can account for both the bulge and LMC rates without recourse to MACHOs in the halo. We also mention that the LMC microlensing rate is small enough that a significant part of it ( $\sim 0.5 \times 10^{-7}$ ) could be due to microlensing by objects in the LMC itself [26].

Our most striking result is that all viable models have a significant halo component. This can be traced to the flat-rotation curve constraint (even though it is very conservative) and the upper limit to local projected mass density [23], and is essentially independent of the bulge optical depth. That is, while  $\tau_{\text{BULGE}}$  provides us with information about the disk and

bulge components of our galaxy, the halo parameters are relatively insensitive to it. This can be seen in Fig. 3, where the local halo density in acceptable models is around  $5 \times 10^{-25} \text{ g cm}^{-3}$  with more or less the same uncertainty as previous estimates (see e.g., Refs. [27]).

Even more than the uncertainty in the observed LMC microlensing rate, imprecise knowledge of the galactic model dominates the uncertainties in determining the MACHO fraction of the halo. However, in most viable models, an all-MACHO halo results in an optical depth to the LMC that is many times that observed (Fig. 2), and a significant nonbaryonic halo component seems indicated (Figs. 3 and 4). The viable models with the largest MACHO fraction have thin disks, small bar masses, large core radii and high local circular velocity.

To summarize: (1) A single component of the galaxy cannot account for both the bulge and LMC events. For example, a spherical halo predicts an LMC rate that is slightly higher than the bulge rate; a thin disk cannot account for either the bulge rate or the LMC rate. A thick disk can explain the LMC events, but not the bulge events. (2) The most promising model for explaining the high bulge rate is an asymmetric bulge (bar) that lenses itself [25] with a lesser contribution from a thin disk. (3) Viable models of the galaxy have a significant halo component and the LMC rate expected for an all-MACHO halo is many times that observed. (4) While the present data cannot preclude an all-MACHO halo, it appears that the fraction of the halo in MACHOs is less than 30%. This is consistent with searches for faint halo stars that indicate that their contribution to the halo mass is small (provided that the mass function of halo stars is “smooth;” see e.g., Ref. [28]).

If the bulk of the halo is not in the form of MACHOs, what is it? While it is not impossible that it could be baryonic, in a more diffuse form, e.g., clouds of neutral gas [29], cold dark matter is a more compelling possibility. In an  $\Omega = 1$  cold dark matter model, the naive expectation for the baryonic mass fraction in our galactic halo is  $f_B = \Omega_B$ . Based upon primordial nucleosynthesis  $0.01h^{-2} \leq \Omega_B \leq 0.02h^{-2}$  [30], which implies  $f_B \simeq 0.04 - 0.2$ . The expected baryon mass fraction for models with an admixture of massive neutrinos ( $\Omega_\nu \sim 0.2 - 0.3$ ) is only slightly higher. For cold dark matter models with a cosmological constant,  $\Omega_\Lambda \simeq 0.8$ ,  $f_B \simeq 0.1 - 0.2$ . If the baryonic halo has undergone moderate dissipation, the baryonic mass the baryon fraction in the inner part of the galaxy can be increased, though it is still expected to compose less than half of the local dark matter density [8]. From Fig. 4, it is clear that the baryonic mass fraction in our halo implied from microlensing is consistent with any of these scenarios which provides further motivation for the ongoing experimental efforts to directly detect neutralinos and axions in our own halo.

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- [21] See e.g., J.N. Bahcall, *Astrophys. J.* **276**, 169 (1984); K. Kuijken and G. Gilmore, *ibid* **376**, L9 (1991). Taking a smaller value for  $\Sigma_{\text{LUM}}$  would allow for larger  $\Sigma_{\text{VAR}}$  and hence larger  $\tau_{\text{BULGE}}$ ; however, taking  $\Sigma_{\text{LUM}} = 0$  only increases  $\tau_{\text{BULGE}}$  by  $0.3 \times 10^{-6}$ .
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- [24] Our expression for  $\tau$  when applied to the bulge implicitly assumes that all the mass density in the disk and bulge is available for lensing. However, the bulge lenses are certainly not bright stars. Zhao et al. [25] find that correcting for this is a small effect. To account for the fact that the lens are unlikely to be bright stars we simply do not include the contribution of the fixed luminous disk to  $\tau_{\text{BULGE}}$ .
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## Figure Captions

**Figure 1:** Optical depth to the bulge for bar masses of 1, 2, and  $3 \times 10^{10} M_\odot$  (bottom to top) and thick (broken) and thin (solid) disks as a function of the local projected mass density  $\Sigma_{\text{VAR}}$  for models that satisfy the kinematic constraints ( $r_0 = 8.5 \text{ kpc}$  and  $v_c = 220 \text{ km s}^{-1}$ ).

**Figure 2:** Optical depth to the LMC from an all-MACHO halo (upper lines) and thick (broken) and thin disks (solid) for bar masses of 1, 2, and  $3 \times 10^{10} M_\odot$  (right to left) as a function of  $\Sigma_{\text{VAR}}$  for models that satisfy the kinematic constraints ( $r_0 = 8.5 \text{ kpc}$  and  $v_c = 220 \text{ km s}^{-1}$ ).

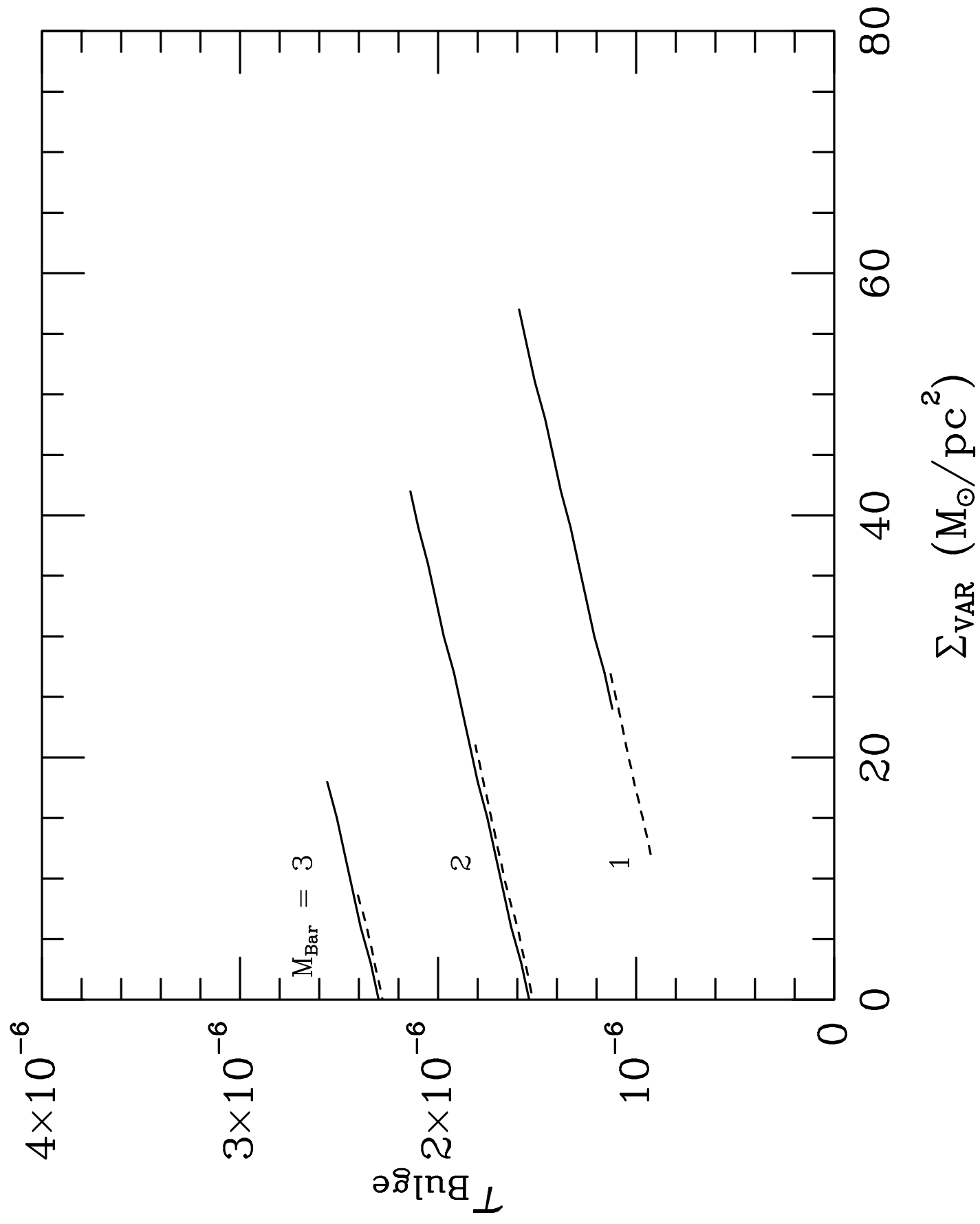
**Figure 3:** Distribution of local cold dark matter density in viable models for  $\Sigma_{\text{VAR}} = 5 - 15$ , 25-35, 45-55, and  $65 - 75 M_\odot \text{ pc}^{-2}$ . Since the halo MACHO fraction in most viable models is small, the local cold dark matter density is approximately equal to the total local halo density.

**Figure 4:** Distribution of halo MACHO mass fraction in viable models for  $\Sigma_{\text{VAR}} = 5 - 15$ , 25-35, 45-55, and  $65 - 75 M_\odot \text{ pc}^{-2}$ .



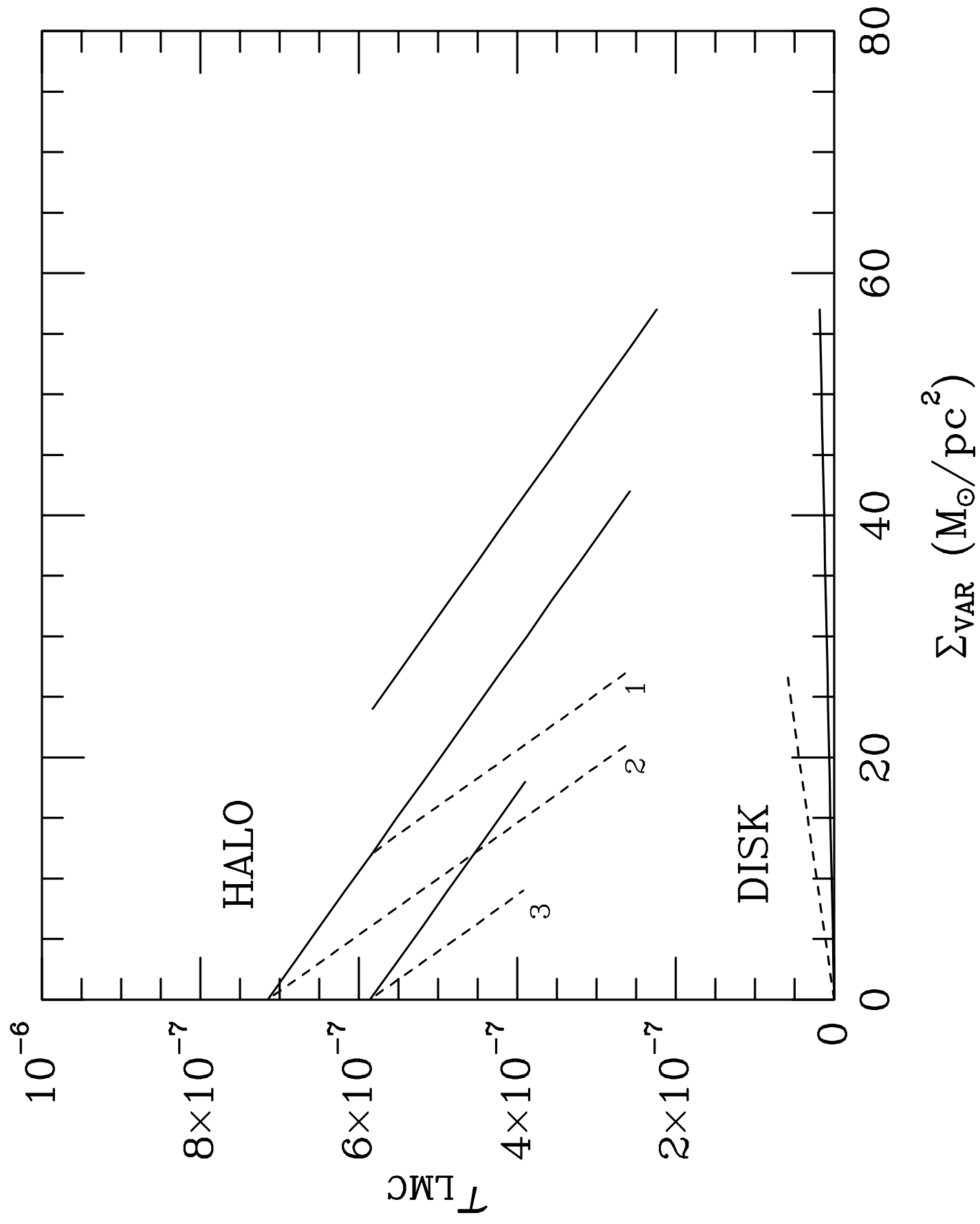
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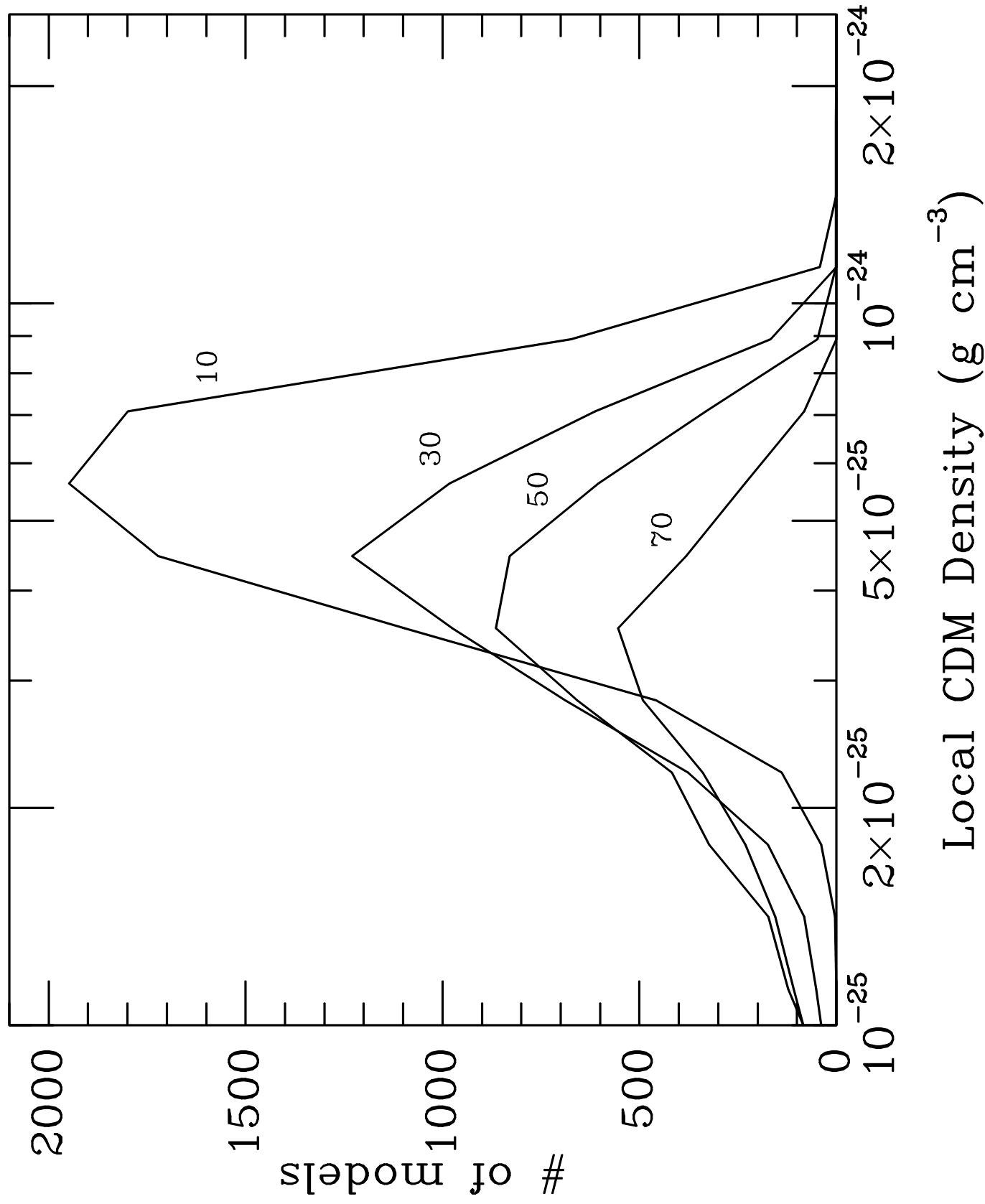
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